Design and Fabrication of A Pencil Shoulder Cutting Device for a Novel Endcap

by

Matthew Paul Hohenberger

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science in Mechanical Engineering

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2013

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Abstract

The pencil shoulder cutting device is a stepper motor driven mechanism to cut a small groove into the end of a pencil, which is needed for a novel seed-capsule endcap for a new pencil called Sprout. The pencil was developed by a team of MIT graduate students, and the shoulder cutting device is one step in an automated assembly process for Sprout.

The device autonomously cuts a 0.0075in. deep shoulder into one end of the pencil using a 0.25in. end mill. The device includes a stabilizing sleeve that reduces vibration of the pencil during machining, and creates a vacuum seal so that chips from the pencil are cleanly removed.

The cutting time for each pencil is 2s, with an absolute accuracy of 3.1×10^{-4} in. for the depth of cut after ten tests with the machine. The capsules fit correctly onto the shoulders when done by hand, and the design will be confirmed once the entire machine is running autonomously.

Thesis Supervisor: David R. Wallace
Title: Professor of Mechanical Engineering

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Chapter 1

Introduction

1.1 Motivation

Sprout is a pencil with a seed in it.[1] It is a product designed and fabricated by a team of masters students in 2.744, MITs graduate product design class, in the Spring of 2012.[2]

Figure 1-1: Sprout, a pencil with a seed inside.

After gaining over 2,000 backers and reaching their monetary goal on the crowd funding website Kickstarter[3], Team Sprout hired Minpack Inc.[4] to manufacture Sprout pencils for them. The team designed jigs to assist in the hand made production of Sprout, and Minpack used these to manufacture the product in batches at a rate of approximately 10,000 per week.

During the process of filling orders from Kickstarter, Team Sprout signed a contract with a European marketing company for 15,000 pencils. While trying to find a similar deal in the US, the team realized they needed to lower their manufacturing costs for the venture to be profitable. They set a goal of manufacturing 30,000 pencils per week through an autonomous device.

After consulting with professionals in the field of mass production, the team decided to build Autosprout themselves. Sprout is a simple product consisting of two parts plus seed. The two parts are symmetric and their connection to one another is simple. Their goal is to have Autosprout complete by mid-May 2013, and with many components to the manufacturing, they invited me to assist in the design. I was given the task of creating the device that would cut the radius of one of the ends of the pencil down by 0.0075in. This shoulder is needed for the seed capsule to fit onto the pencil.

Figure 1-2: The shoulder that has been cut in a Sprout. The diameter of the shoulder is critical for the seed capsule to fit correctly.

1.2 Sprout

1.2.1 The Product

Sprout is a pencil that grows into a plant after it becomes too small for use and the user plants it in the ground. Its purpose is to create a fun and beautiful environment in the classroom and office and to encourage kids to become more interested in nature and the outdoors.

Sprout is made from a Ticonderoga cedar pencil with a water-activated end capsule filled with a seed, organic material, and fertilizer. As can be seen in Figure 1-3 below, the pencil is labeled using a laser etching machine. All pencils have the plant type and the Sprout logo etched into the wood. Sprout comes in a variety of plant types, from herbs, flowers, vegetables, and more.

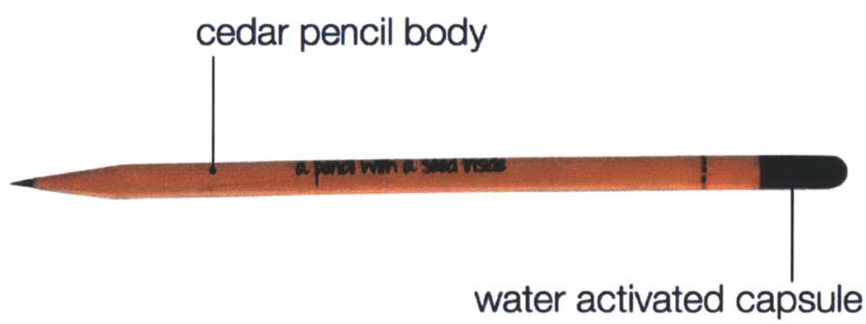

Figure 1-3: The features of Sprout.

Once the pencil has been fully used and needs to be discarded, the user can simply plant the rest of the pencil and the capsule into a pot with soil, water it, and watch their plant grow. An example of this can be seen in Figure 1-4 below.

Figure 1-4: Sprout is planted when it becomes too short for use and watered so the seed capsule will dissolve and the seed will germinate.

1.2.2 Current Manufacturing

The manufacturing of Sprout is a five step process. The first step is cutting a 0.0075in. deep shoulder into one end of the pencil, 0.25in. in length. Then a small amount of non-water based glue is added to the shoulder so that the seed capsule, which has been filled with seed and soil during the cutting process, will adhere to the pencil. Finally, the Sprout logo and seed type are laser etched onto the pencil.

1.2.3 Hand Turned Shoulder Cutter

Team Sprout created different jigs with which Minpack could easily perform each task in the process. The device that cuts the shoulders into the pencil can be seen below. The user turns on the hand drill, sticks the pencil into the Teflon slot until it hits a set screw, and rotates the pencil completely. As the pencil rotates, a quarter inch end mill cuts the shoulder into the pencil. The device is attached to a vacuum to remove the sawdust from the cut.

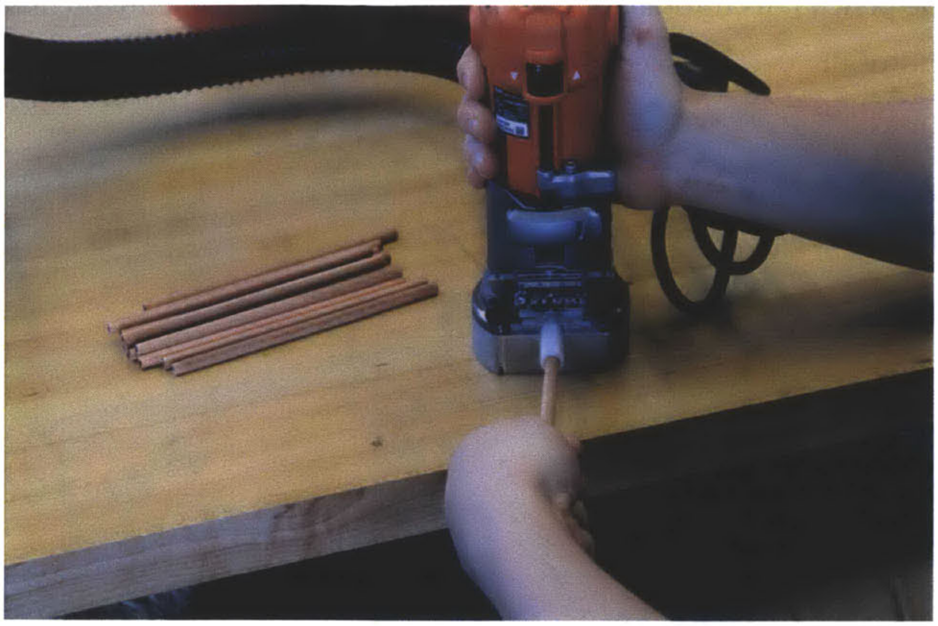

Figure 1-5: Cutting the shoulder for Sprout by hand using the jig built by members of the Sprout team.

1.3 Autosprout

Autosprout is an automatic Sprout manufacturing machine. Figure 1-6 below shows the main frame of the plant. The two main bases, made out of 80/20 aluminum stock, houses all of the components for manufacturing. One of the structures contains the majority of devices, while the second one contains a vibratory feeder that aligns the seed capsules properly. Hundreds of pencils will be loaded into a hopper, picked out individually by a star wheel feeder, rotated vertically, and slid into one of the slots in a pencil carousel. The carousel, which has 8 slots for pencils, rotates 45 degrees, lowers down for all of the pencils to be worked on at their respective stations, moves back up, and repeats the process. There is a laser branding station, the shoulder cutting station, glue station, and finally a station that lowers the pencil down to connect to a seed capsule. There is a parallel process that orients the seed capsules, fills them with seed and soil, and places it in the correct position to be attached to the pencil.

The pencils are held in the carousel by a spring loaded vice. When the pencil first falls out of the hopper and into the carousel, a pneumatic pushes the vice open so that the pencil falls through and is clamped in when the pneumatic is released. At the end of the cycle, a second pneumatic pushes the vice open again and lets the finished Sprout fall out.

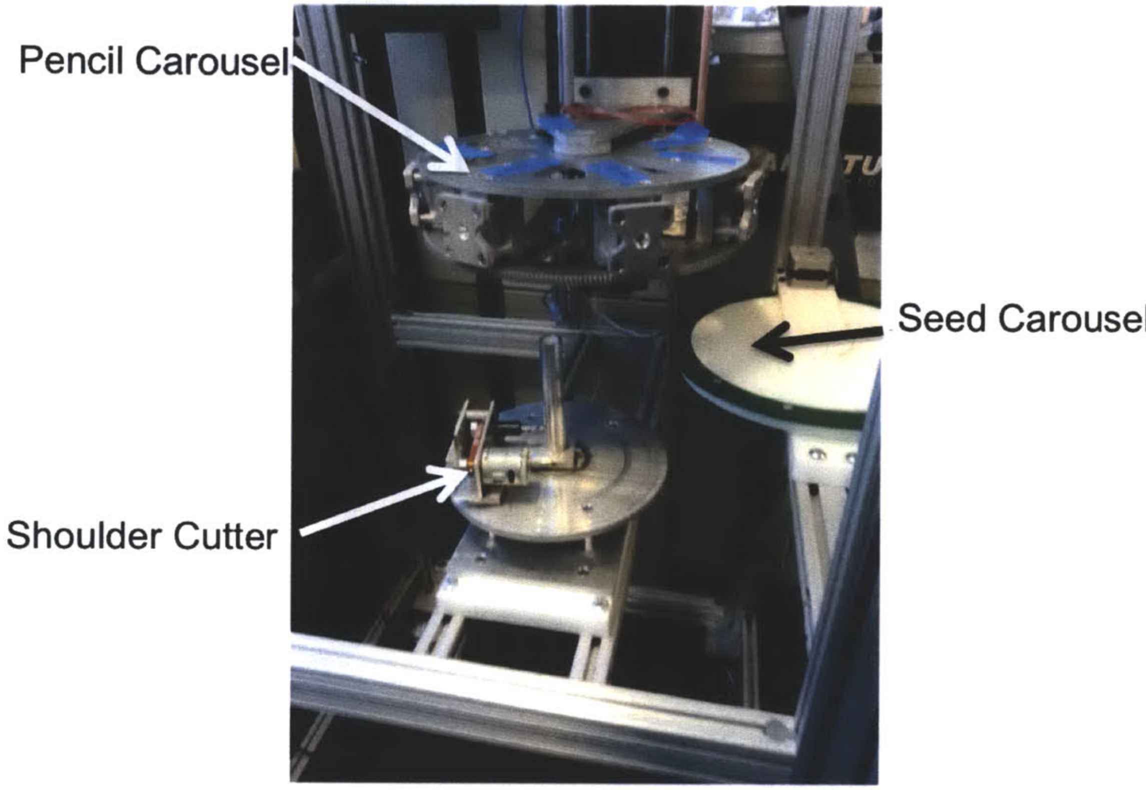

Figure 1-6: The main base of Autosprout. The pencil carousel, seed capsule carousel base, and the shoulder cutter can be seen.

Chapter 2

Autonomous Shoulder Cutting Design

2.1 Requirements

The design of the shoulder cutting device is of critical importance to the fit of the connection between the pencil and the seed capsule. The functional requirements for the shoulder cut station are as follows:

- Performance: Consistently and accurately make a cut of 0.0075in. depth into the pencil. The cut should be located at one end of the pencil and end with a 90 degree shoulder at a distance of 0.25 in. along the length of the pencil.
- Electronic Control: Control of the stepper motor that turns the cutting device is required to ensure a complete cut around the entire pencil.
- Actuation speed: The speed of the cut should be fast enough to make a complete cut by the time the carousel lifts up and moves onto the next station. This time is approximately 3s.
- Chip removal: The vacuum attached to the device should take away the chips from the pencil out of the cutting area and keep the whole assembly free of wood shavings.

2.2 Cutting Techniques

During the design and manufacturing of Sprout, a quarter inch end mill was used to cut the shoulder into the pencil. The end mill was suitable for the manual manufacturing device, but the pencil is stationary in the pencil carousel vice and additional options were explored to create the shoulder.

2.2.1 Wood Plug Cutter

A drill press wood plug cutter was tested on the pencils. The tools main purpose is to cut into blocks of wood and create wood dowel pins. The pencil was placed in the lathe and the plug cutter was placed in the tailstock. This created a best-case scenario of cutting with minimal deflection of the pencil during the cut. The cutter made a clean cut over a large majority of the pencil, but it created large chips that remained stuck to the pencil as can be seen in Figure 2-1 below. These chips are not favorable for the production of Sprout and the plug cutter was not used in the design for Autosprout.

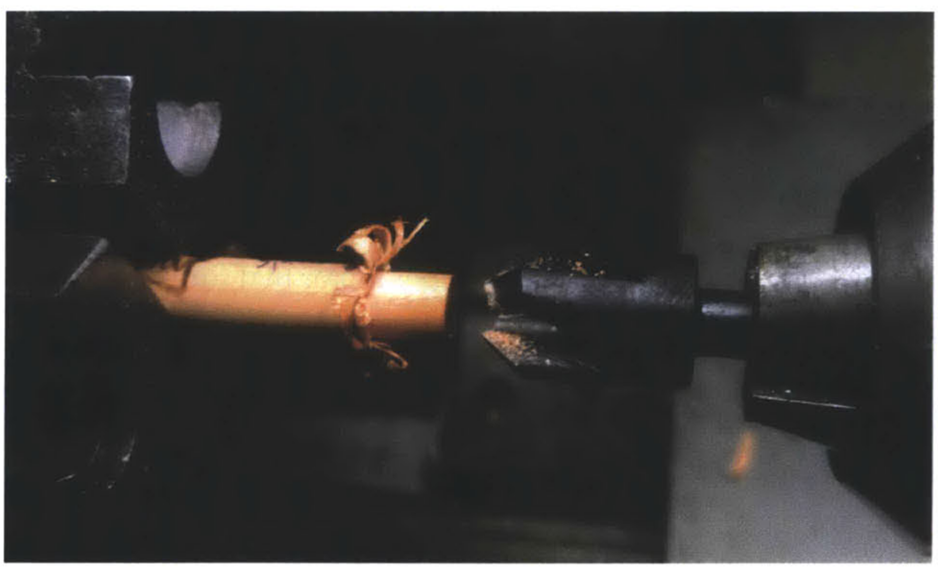

Figure 2-1: The plug cutter being tested in the lathe. The cut doesn't create a clean shoulder and is not suitable for Sprout.

2.2.2 Crimp

A second option that was tested was squeezing the end of the pencil down. This was a favorable option as it could be automated easily and the process would be very fast. An appropriate sized hole was drilled through an aluminum block. The block was then cut in half and attached to a pair of wire crimpers. The pencil was then placed in the crimp and squeezed. The device created a shoulder, as can be seen in Figure 2-2 below, but the shape and quality of the shoulder was not clean or consistent and could not be used in the autonomous production of Sprout pencils.

Figure 2-2: The crimp attachment to a pair of wire crimpers. The did not consistently create a clean shoulder.

2.3 Low Cost Design

A driving factor in the design of the shoulder cutting device was the limited budget allotted to its fabrication. Although a monetary value was never listed, the instructions where to use as many scrap parts as could be found in assorted part boxes in the Media Lab. Both the motor used to drive the drill bit and the stepper motor used to turn the bit around the pencil were found in the lab. The bearings, end mill, and all material used in the design were already in the lab as well. Although these parts set restrictions on the design, the use of in-house parts drove the design and fabrication time down.

2.4 Actuation

The requirements at the beginning of designing the shoulder cutter were that the pencil carousel was at a fixed height and each of the stations would be pneumatically actuated upwards to perform its function at the bottom of the pencil. As will be explained later, the performance of the first design of the shoulder cutting station was not satisfactory due to this actuation requirement. Consideration of this as well as the cost of individually actuating several stations, it was decided to actuate only the pencil carousel downwards. A ball screw actuator carries the pencils downwards to the correct level of the workstations where each device performs its task on the pencils.

2.5 Design

Keeping in mind the goals for the device and the requirements to fulfill those goals, the shoulder cutting device was designed as seen in Figure 2-3 below. The design was created to be as simple as possible while having a small footprint. It was also designed to easily change out the gearing ratio for the stepper motor and center pencil holder in case the friction between the pencil and the holder was too great and stalled the stepper motor. The design also allows the end mill to be moved radially in order to adjust for any inaccuracies during manufacturing and ensure the depth of the shoulder is cut correctly.

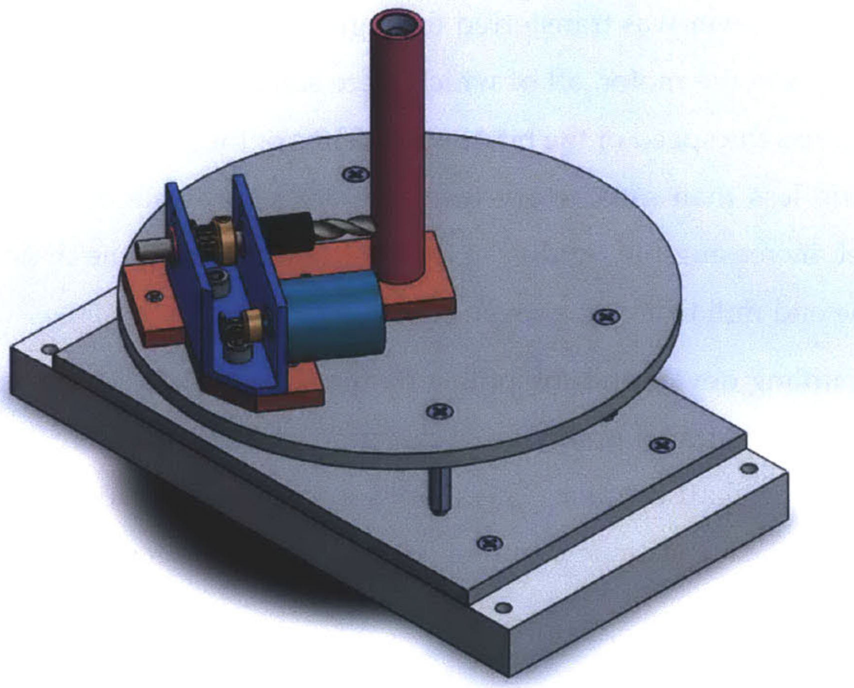

Figure 2-3: Final Solidworks design of shoulder cutting assembly.

2.5.1 Cutting Assembly

The shoulder is cut into the pencil using a 0.25 in. Onsrud carbide end mill. Its initial length was 2.5 in., but to make the assembly more compact, and thereby reducing the structural loop of the design, the bit was cut down to 1.5 in. Although the bit could have been further cut down, some of the shaft had to remain so that the set screw in the rigid coupling device could securely clamp down the tool. Trying not to ruin any of the tools in the shop in the process of cutting down the carbide bit, the water jet was used. The water jet was only able to make a small cut in the tool, but due to the brittleness of carbide it was cleanly broken apart after a light strike with a hammer.

On the other side of the coupling device was a 0.25 in. steel shaft, supported by two bearings in the walls of a 1x3 aluminum tube extrusion that was cut down to a 1x2 U-channel. There was a spare DC motor in the lab that, after a quick mockup, confirmed that it would be able to turn the end mill fast enough to make a clean cut in wood. The DC motor was purchased from Jameco, and its part number is 232101.[5] The power was transferred through a timing belt and pulleys that were found alongside the motor, all of which were scrap from a previous project. The pulleys geared the speed of the bit down 9/25ths of the motor speed. After testing and finding less than satisfactory results, a spacer was added to the top of the U-channel, increasing the rigidity of the base and reducing the deflections which caused the end mill to create uneven cuts.

The coupling device and the pulley fix the shaft radially in the assembly. The end mill is able to travel in the radial direction and is then clamped down by the set screw in the shaft coupler. This allows for adjustments to the location of the end mill to make an accurate depth of cut into the shoulder of the pencil.

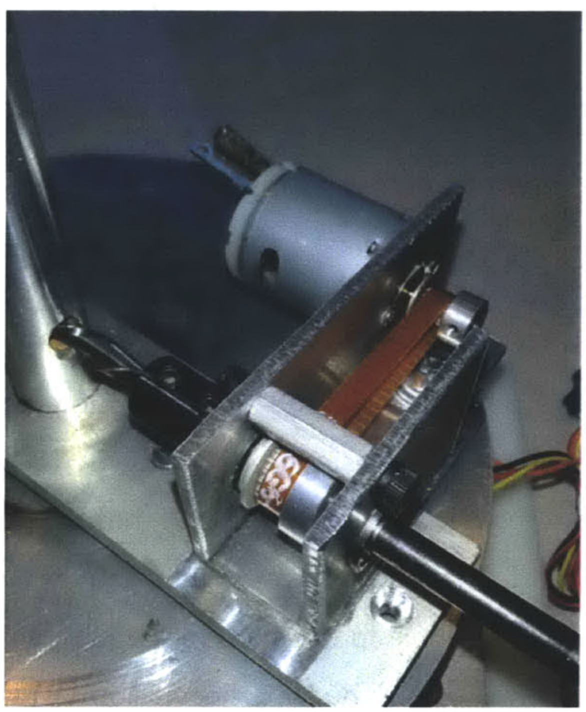

Figure 2-4: Final design of the cutting assembly.

2.5.2 Pencil Sleeve

The pencil sleeve was redesigned after first round testing. The system requirements at the beginning of the project called for the shoulder cutter to be actuated upwards to the pencil holder. A pneumatic actuator was chosen because its quick actuation speed was favorable over the linear motors available in lab. The pencil sleeve was designed around the pneumatic actuator's one inch stroke length. Once fabricated, the system was tested by holding the pencil in a vice and spinning the pencil sleeve and end mill around the pencil. The results were not desirable and attributed to the small proportion of the pencils length that was in the sleeve. Figure 2-5 below shows the unclean cut from the tests of the first pencil sleeve.

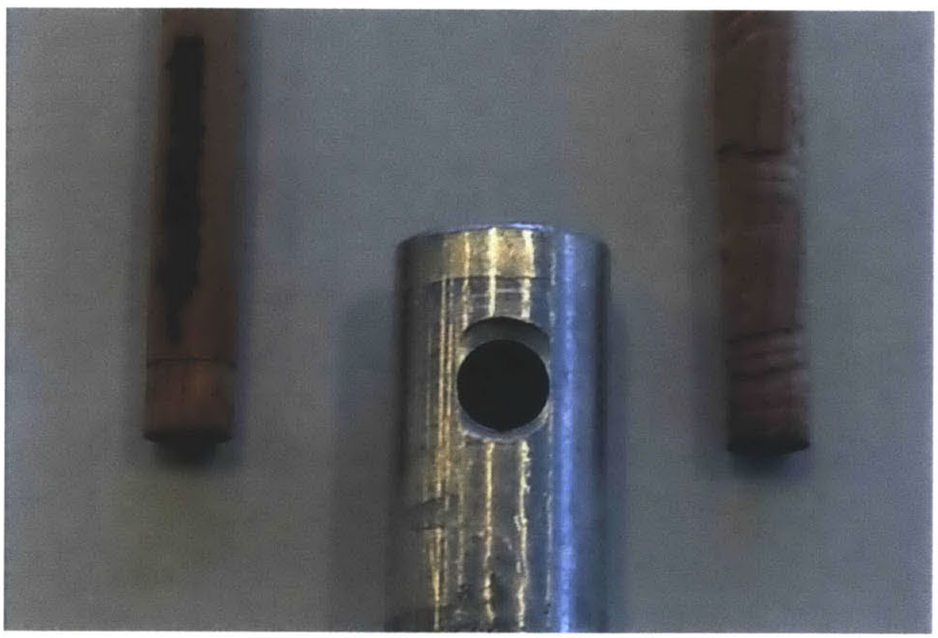

Figure 2-5: Difference in quality of cut between the hand made shoulder cut and the cut from the first pencil sleeve.

The part was redesigned, this time with a 3in. flute length compared to a 0.3in. flute. The second change to the design was the insertion of a Teflon sleeve inside of the aluminum. This was done to decrease the diameter of the flute and create a better fit with the pencil to reduce vibrations of the pencil inside of the sleeve and create a more uniform and accurate shoulder cut. The mean diameter of the pencils being used is 0.288 ± 0.002in. The closest bit in the shop to cut the flute was

0.3in. The aluminum sleeve was bored out and then a 1/2 inch router bit cleaned up the flute. After the 1/2 inch rod of Teflon was not able to be press fit into the aluminum by more than an inch, it was placed into a container of liquid Nitrogen, shrunk down to a small enough size, and easily slid into the aluminum sleeve. Once the Teflon returned to room temperature, it expanded and created a tight bond with the aluminum. The whole device was then placed back into the lathe and the Teflon was bored out. The stress on the Teflon from the tight fit reduced the size of the hole from 0.3in to 0.29in. The aluminum and Teflon sleeve part can be seen below in Figure 2-6.

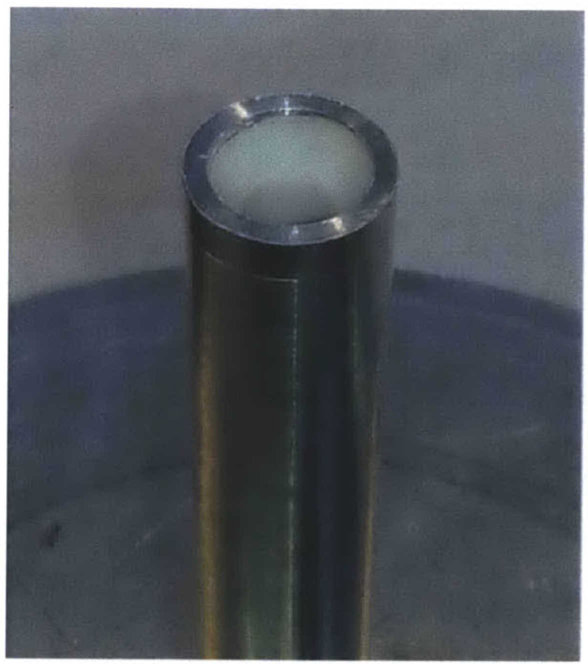

Figure 2-6: Aluminum and Teflon Pencil Sleeve.

The new pencil sleeve produced a cleaner cut and sharper shoulder in the pencil during testing runs of the assembly. The seed capsules were able to fit on the pencils with more ease than before with the shorter sleeve. A comparison of the shoulder cut from this device compared to the cut from the hand turned device can be seen in Figure 2-7 below.

Figure 2-7: Comparison between the hand turned device and the automated device.

2.5.3 Chip Removal

One of the functional requirements for the design was that the device must have a way to quickly remove the sawdust from the cut. The assembly was designed for the chips to fall through the flute of the pencil holder. For most effective results, the assembly had to create as close of a vacuum within the flute. Because of this, the opening in the side of the pencil sleeve for the end mill to access the pencil had to be as small as possible. The tight clearance created difficulty in assembly, as many times the end mill got jammed in the wall of the pencil sleeve, but with careful assembly the bit can turn without interference.

In the first design, the base of the assembly was an aluminum plate that was attached to another plate by spacers. This space in between the plates housed the gears that attached the pencil sleeve to the stepper motor. However, this design did not create a vacuum within the flute. The final assembly was redesigned using a delrin block that had features milled out so that the top surface of the delrin created a seal with the top aluminum plate. A hole was milled out in the bottom of the delrin for the vacuum nozzle to be press fit in. This delrin block can be seen in Figure 2-8 below. The current ratio of the gears is 1:4 from the stepper motor to the pencil sleeve. There is room in the delrin block for gears that go up as high as 1:7. This was built in as the stepper motor has shown to stall when friction in the system becomes too high. Grease will be added at some of the major friction locations to reduce the stalling.

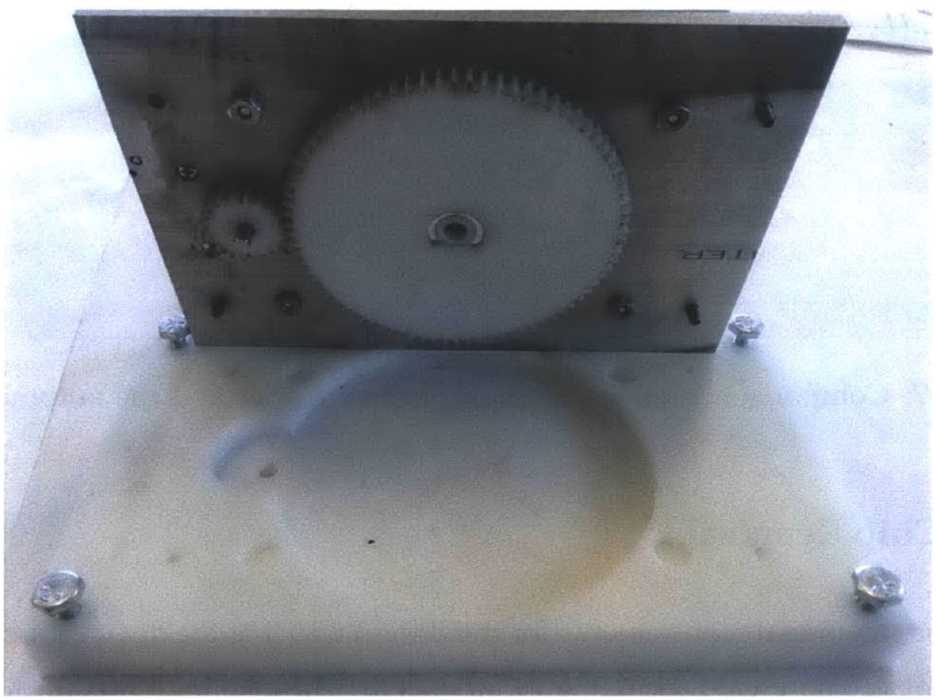

Figure 2-8: Delrin block without the vacuum hole. The delrin block helps create a chamber for a vacuum to form and the chips to be cleared away.

2.5.4 Rotation of Cutting Assembly and Pencil Sleeve

The cutting assembly was attached to an aluminum plate that had a hole for the pencil sleeve. The hole was made to be a close fit for the pencil sleeve, and the two get held together by three set screws as can be seen in Figure 2-9 below. These set screws can be easily adjusted to change the orientation of the pencil sleeve with respect to the end mill, as sometimes they are not aligned correctly and the bit gets jammed on the walls of the access hole.

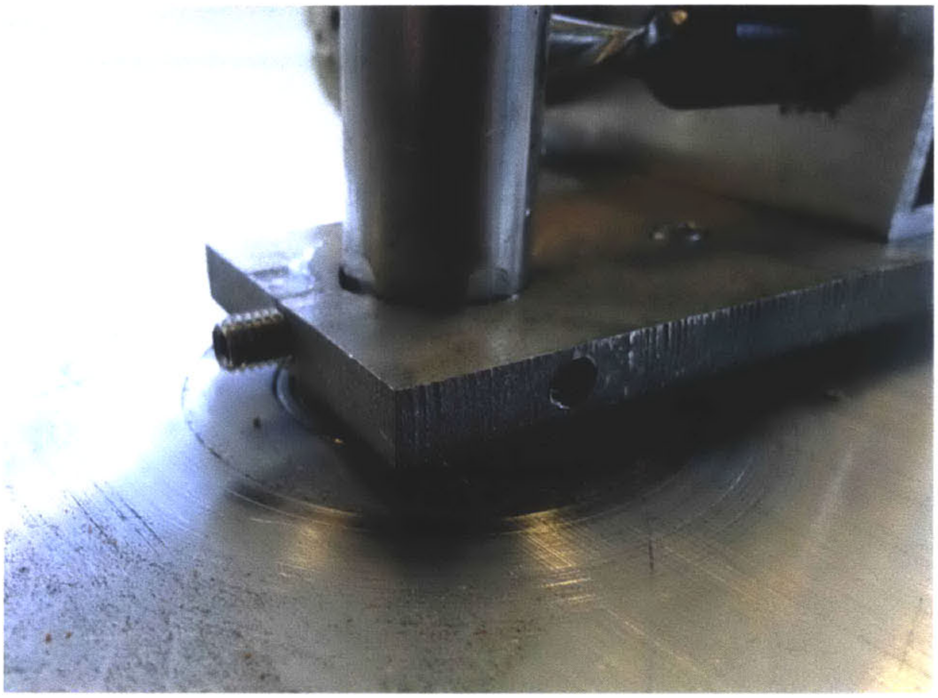

Figure 2-9: Set screws hold the cutting plate to the pencil sleeve.

A small, Teflon disk is attached to the bottom of the cutting plate and runs along the top surface of the circular aluminum plate. This small disk supports the load of the cutting assembly so that the set screws do not have to. The torque from the cantilever could move the screws out of place and the end mill would become misaligned.

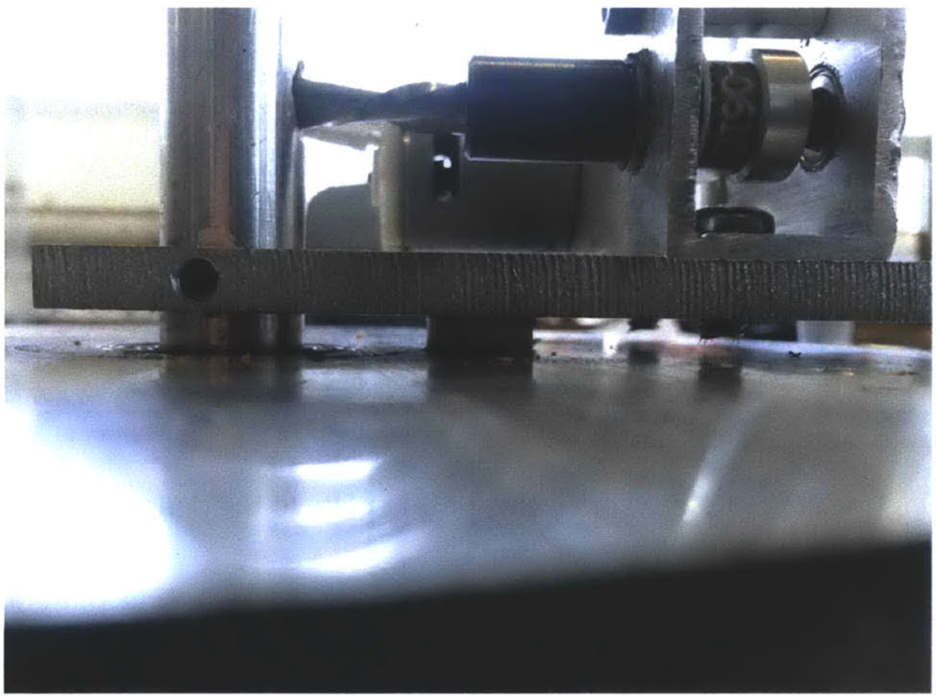

Figure 2-10: The Teflon disk carries the weight of the cutting assembly. The disk is close to the center of rotation to reduce the torque caused by friction.

Chapter 3

Results

The automatic shoulder cutting machine was attached to the Autosprout frame as can be seen in Figure 1-6. The pencils were placed in the carousel and positioned correctly so that they would lower into the pencil sleeve. The pencil carousel was moved by hand, but the shoulder cutting device ran using an open loop control to turn the stepper motor and end mill. After finding the correct depth of cut for the pencil, ten pencils were cut and the seed capsules were able to fit onto the shoulders. The cutting time for each pencil is 2s, with an absolute accuracy of $3.1\text{x}10^{[-4]}$ in. for the depth of cut after ten tests with the machine. The figure below shows multiple pencils and their depth of cut as the end mill was moved back slightly after each test until the correct depth of cut was made.

Additional tests will be performed to ensure robustness of the system. The carousel will be positioned slightly off center to test how well the chamfer at the opening of the pencil sleeve works. This will also create greater friction between the Teflon flute and the pencil, and the stepper motor is required to overcome this friction. Finally, the device will have to be tested in operation with all of the other elements in the system.

Figure 3-1: The end mill position was set by running multiple cuts and testing their size with a seed capsule.

Chapter 4

Future Works

The autonomous shoulder cutter has room for improvement that will be made in the near future. One of the problems comes from the end mill. Although the end of the shoulder is clean, the body of the shoulder has a bulge in it that makes it difficult to fit the capsule securely on. A three flute end mill has been purchased in order to create a flatter cut.

The second change that will be made is in the assembly of the cutting assembly. The three flute end mill is 3 in. long and can fit through both bearings while still cutting the pencil. This will eliminate the shaft coupler from the design, so there will be a set screw at the end of the bit which will accurately control the depth of cut. The base which holds the bearings and motor will be milled out from a 1 in. block of aluminum so that the walls will be thicker. This will help the bearings be more concentric, as the current holes became misaligned due to deflections of the structure.

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Bibliography

[1] http://www.democratech.us/sprout/

[2] http://web.mit.edu/2.744/www/index.html

[3] http://www.kickstarter.com/projects/democratech/sprout-a-pencil-with-a-seed

[4] http://www.minpack.com/

[5] http://www.jameco.com

[6] Boothroyd, G., Assembly Automation and Product Design, Wakefield, Rhode Island, 2nd Edition, 2005, (272-276)

[7] Conversations with Benjamin Peters, Mediated Matter M.S. candidate 2013